Aggregation of Small-Scale Active Resources for Smart Grid Management

Antti Koto, Shengye Lu, Turo Valavaara, Antti Rautiainen and Sami Repo

***Abstract*—This paper describes a smart grid demonstration environment developed for concept testing of multiple smart grid applications that are based on utilization of small-scale active resources. The laboratory environment consists of utility control centre systems, aggregator software, a home energy management system, and interfaces between the systems. Two applications called frequency dependent load shedding and monitoring of reserves are demonstrated and analyzed in the paper. The results show that the developed demonstration environment is suitable for concept testing of different smart grid applications.**

***Index Terms*—power system control, smart grids, load management, information systems, data communication**

I. INTRODUCTION

The idea of the smart grid is to integrate all kind of active resources to the operation of electricity market and networks. These resources, including distributed generation (DG) units, remote-controllable loads, and energy storages, can be located anywhere in the grid. Active resources can be seen as distributed energy resources (DER) that the smart grid management can utilize for multiple purposes. Ultimately, all applications in the smart grid management serve the same goal, which is to increase the degree of automation in electrical networks in order to enable significant utilization of more environmentally friendly energy solutions, such as renewable generation, electric vehicles (EV), and active energy saving. Small-scale active resources offer one currently unused possibility for the electrical energy domain to reach this goal.

The utilization of small-scale resources is becoming economically profitable due to rapid development of information and communication technology (ICT). Furthermore, the needs for smart grid applications utilizing these resources are becoming evident. These needs are:

- Large-scale resources are already utilized or the cost of resources is extremely high
- Operation of electricity market and networks is becoming more challenging due to the growth of uncontrollable power production and new type of loads
- New services are going to be offered to customers
- New parties are entering to the electricity business
- New business models are adopted

The ICT demonstration environment described in the paper is designed to be suitable for multiple smart grid applications. The profitability is strongly based on cost sharing between several applications. The demonstration environment consists of distribution network operator's (DNO) control centre software (i.e. supervisory control and data acquisition (SCADA) system and distribution management system (DMS)), aggregator software, a home energy management system, and interfaces between these systems.

The paper is organized as follows: Section II presents the ICT architecture of the developed demonstration environment, whereas section III describes two use cases, frequency dependent load shedding and monitoring of reserves, which are demonstrated and analyzed. After this, demonstration environment and results are described and discussed in section IV. Finally, section V describes future work and section VI draws a brief conclusion.

II. ICT ARCHITECTURE

The integration of information and automation systems is the key enabler of the smart grid. Fig. 1 represents an overview of information and automation systems fulfilling the gap between small-scale resources and the existing utility systems. The utilization of small-scale resources in the upper level information systems requires aggregation of information. To fulfil this requirement, aggregator software, which acts as a centralized information source to existing utility systems, is needed. The aggregator should be extremely reliable and have high availability when critical smart grid management applications are utilizing its information. It is quite natural to think of the aggregator as a sophisticated SCADA system for small-scale resources.

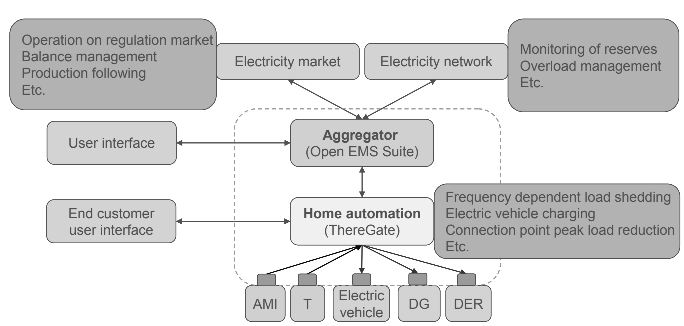

Fig. 1. Integrated information and automation systems.

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The second part of the new information and automation system is the home energy management system (i.e. home automation). This is a gateway to multiple resources and also a place for local decision making. Application examples for the home energy management level are listed in Fig. 1. In order to communicate with a resource, there is a need for an interface at the resource side. In practice this is probably the trickiest part of the whole system because the interfaces to existing resources require tailoring. All measurements are collected to the home energy management system and also decision making is mainly located there.

Communication between the aggregator and the home energy management system is based on Web-based data transfer technologies: extensible markup language (XML) messages and hypertext transfer protocol (HTTP) queries. In order to reduce the number of messages, an asynchronous message exchange pattern and event based messages, initiated by e.g. status change of a resource, are exploited as much as possible. Communication media between the systems can be anything that is based on standard transmission control protocol / Internet protocol (TCP/IP) family. For example, in our demonstration environment the data transfer uses Ethernet based local area network (LAN), whereas in a real environment wireless technologies (e.g. 3G/4G) could be used.

The ICT architecture is designed to be suitable for the needs of near real-time smart grid applications, where communication delays can vary from a few seconds to a couple of minutes. Therefore, very time critical applications, such as network protection functions, are not supported by the system. The ICT architecture itself is general and could be implemented with any suitable software products and TCP/IP based communication solutions. Our demonstration environment represents one possible implementation of the presented ICT architecture, utilizing selected commercial software products and Web-based data transfer technologies.

A. Information Aggregation

The aggregator is a centralized information integration, storage, and analysis tool for different kind of smart grid applications. It collects and stores all kind of operational information, such as control commands, queries, measurements, events, and alarms, to its database. In our demonstration environment we have chosen a commercial software product, Open EMS (Element Management System) Suite (OES), as the aggregator software. OES is an operation support system platform developed by Nokia Siemens Networks [1]. It provides out-of-the-box support for fault management, performance management, and configuration management for any kind of elements that need to be monitored and controlled. In our demonstration environment, the elements, which are monitored and controlled, are home energy management systems and small-scale active resources.

Communication between OES and the home energy management system is realized with a customized software agent. The agent retrieves measurement data from the home energy management system once per minute via HTTP queries. After receiving new data, the agent compares retrieved values with earlier values. If the values have changed enough, the agent creates new XML files, which are sent to OES through simple object access protocol (SOAP) as new messages. As a result, all near real-time measurements and parameters of the small-scale active resources are stored in the aggregator's database. The aggregator's role is then to combine the received data to aggregation results, based on predefined and application specific algorithms. In the demonstration environment, we do the aggregation by utilizing the built-in performance management platform of OES.

In the demonstration environment, the agents are running on separate computers in the same LAN, where each agent is controlling its own home energy management system. In a real environment, a natural location for agents would be computers at secondary substations. Each secondary substation would have one computer with multiple agents to control all the home energy management systems connected to the same low voltage network. This type of hierarchical architecture would also enable new low voltage network level automation applications at secondary substations [2].

B. Home Energy Management

In addition to finding new, more efficient, and environmentally friendly energy sources, reducing energy consumption and slowing its growth is also highly important. Home energy management offers new possibilities for energy saving, and is therefore an important part of the future electricity networks. It has two different aspects: on one hand it gives the customer an opportunity to monitor and control energy consumption efficiently and on the other hand it delivers information to network operator and even enables remote control of household energy resources.

Home automation and smart home systems can collect data from the energy consumption of a household. When a customer sees the statistics of the energy consumption, it becomes easier to realize where to save money and electricity. Getting some concrete information about energy consumption may encourage the customer to turn off and unplug electric devices when they are not needed, like unplugging the television for night, shutting down unnecessary lights and reset indoor temperature. Home automation system gives the customer also extra value, as it enables monitoring and control of some electric devices remotely, using for example a mobile phone or a computer.

Smart home systems are also an essential part of smart grid. Network operator must get more detailed information about the usage of the network than today, and also to be able to control customers energy consumption when needed (this kind of operation of course needs an agreement from the customer side). Smart home systems will be especially important when the number of electric vehicles starts growing. Charging of EVs would preferably take place when the loading of the network is low. Customer would want just to plug the car to a socket and be sure that the battery is full when the car is needed again. This means that a system is needed that will make the decisions about the scheduling of charging, basing the decision on the information about when the car is needed again. Smart home systems can enable this kind of functionality. Furthermore, these systems could make it possible to even use the EV as an energy source in the case of power failure in the network to supply energy for the household (vehicle-to-home, V2H) or to the grid (vehicle-to-grid, V2G).

There are some downsides with the home automation systems. Currently, various manufacturers and different home automation packages for different customers and purposes are not providing any readily usable infrastructure. Another problem is the prices of the smart home systems. The systems are still quite expensive, and many customers may feel that the cost is too high for the benefits they would get out of it. Fact is, that in the future the electricity market and network operators would benefit of widespread home automation architecture more than the customer, so it could be necessary for them to take part to the automation system costs or even offer the whole system to customer and also show that the customer will get some real benefit for participating to the smart grid. This might not be very easy task.

In our demonstration environment, we use a commercial home energy management system known as ThereGate, which is manufactured by There corporation [3]. ThereGate is wireless local area network (WLAN) router based on a Linux based platform with open interfaces and a software engine. It communicates to OES through its built-in Web server. The communication media between ThereGate and the aggregator can be Ethernet, WLAN or 3G. The communication to local energy resources is realized via wireless Z-Wave technology.

C. Integration to SCADA/DMS

The aggregator enables various new applications for utilities (see Fig. 1). These applications extend the scope of distribution automation from the medium voltage network to the low voltage network. As a result, utilities can offer new services for customers, reduce and/or postpone network investments, improve network monitoring and control, and reduce losses. In order to fully utilize these benefits, sophisticated integration between the aggregator and the SCADA/DMS is needed.

The aggregator should provide new information and control possibilities for the utilities' control centres without overburdening the data transfer and processing capabilities of the SCADA/DMS. Furthermore, the integration solution should be as standardized, open, platform-independent, and reliable as possible. As the aggregator communicates directly to the control centre, also information security and real-time abilities are essential. Based on these requirements, the OPC Unified Architecture (OPC UA) data transfer technology was selected and implemented into the demonstration environment.

The OPC UA is an improved version of the well-known OPC specifications, which are widely used in the automation domain [4]. The OPC specifications, as well as the OPC UA, can be used to transfer real-time data, alarms and events, and historical data between control devices and top-level control systems. Both technologies are based on server-client-architecture. Compared to the OPC specifications, the OPC UA enables platform-independence, built-in information security features, and web based communication. The OPC UA is standardized as the IEC 62541 standard series.

In our demonstration environment, we use a customized OPC UA client program at the aggregator side and a commercial OPC UA wrapper/server at the SCADA side. The customized client retrieves aggregation results from the aggregator's database through structured query language (SQL) queries once every 30 seconds, and transfers the values to SCADA through OPC UA.

III. Use Cases

A. Frequency Dependent Load Shedding

The fundamental frequency of the voltage of the power system works as in indicator of the balance between power production and consumption. Frequency decreases if the total power production in energy conversion processes of power plants is less than total energy consumption in the system. And vice versa: in the case of power surplus frequency rises. Today frequency is used to adjust production of power plants in order to maintain the balance between power production and consumption. Some big industrial loads are also used to maintain the balance by disconnecting them from the grid during a grid disturbance.

In addition to large industrial loads, a great amount of small domestic loads could technically be used as a frequency controlled reserve. Loads can be controlled based on local frequency measurements, and loads can be controlled in accordance of frequency in many ways. Some concepts and results concerning for example refrigerators [5], space heaters [6] and electric vehicles [7] are available.

The home energy management system could be used to control different loads in accordance of frequency. Local frequency can be measured from the network, and different loads can be controlled adjusting the setting values of thermostats of thermal loads or directly disconnecting loads from or connecting loads to electricity network. In some cases, as presented for example in [7], it is possible to adjust the power of a load in continuous manner. If an electric vehicle is capable of feeding energy to the grid, it is possible to start feed power and adjust feeding power in accordance of frequency.

B. Monitoring of Reserves

Power system reserves are controllable resources to balance system frequency and voltage in normal and disturbance conditions. Large-scale reserves from power plants, industrial loads and transmission system operator's (TSO) own reserves are part of power system automatic control and protection system. The cost of automation system per resource is not a big question due to importance of reserves and small number of resources. Small-scale reserves are typically controllable loads like EV charging, space heating, and hot water boilers, which include some type of energy storage in order to minimize the discomfort for the customer.

The real-time supervision of reserves, which is currently mandatory for large-scale reserves, requires enormous investments on the ICT system for small-scale resources. However, many automatic reserves may be operated based on local measurements, like frequency or voltage, which are measure of active and reactive power balance, respectively. The operation of reserves does not require real-time communication to the TSO control centre. Nevertheless, the system should be designed so that the reliability of power system is not compromised. The monitoring of reserves is needed to fulfil this obligation.

The proposed design of the ICT system is based on facts which are true for large number of small-scale resources. When number of resources is large, the unavailability of single or even few resources is not critical from the power system viewpoint. The capacity of resources could be forecasted by statistical methods quite accurately thus there is no need for real-time monitoring of reserves. The collection of measurement data from all resources may be slower and for statistical analysis purposes it might be done much later. Also the report from the disturbance situation and resource's actions should not be send until the disturbance is over.

TSO wide monitoring system should also have several hierarchical levels which are monitored with e.g. increasing delay towards the small-scale resources. For example, TSO's SCADA could get information from the aggregator every 5 second. When the aggregator is utilizing a common ICT system with a distribution network company it gets information e.g. from the primary substation automation system every 15 second, which get information from the low voltage network automation system every 30 second or when the capacity of resources has changed enough. Home energy management sends information to the low voltage network automation system every time when the status of a resource is changed. Hierarchical system provides not only non-real-time monitoring data but also short- and long-term statistical forecast of resources. Statistical forecasting should be done at the level where information is accurate (real-time) enough and statistical summation is smoothing out the effects of individual devices. Here it is assumed that this level is the aggregator.

Utilization of common ICT infrastructure with a distribution network operator offers several benefits compared to the situation where an aggregator implements its own ICT architecture. The benefits gained from the utilization of ICT architecture of the distribution automation system include reduced ICT costs, possibility to transfer data in real-time, possibility to implement decentralized automation concept, and possibility to easily detect congestion problems caused by electricity market based controls. A different type of system, where several aggregators operate resources at the same distribution network area, would be very complex from the congestion viewpoint. However, other aggregator concepts are also available.

In addition, it is useful to know what kinds of reserves are available. This information may be get from the aggregator's database where contract details are stored. Reserves are classified as normal and disturbance reserves and also classification according to response time is used for disturbance reserves. Frequency dependent load shedding is also classified for different frequency thresholds thus the reserve capacity of each threshold should be known.

IV. Demonstration

A. Demonstration Environment

The laboratory demonstration environment includes both the information and automation systems as well as the devices, which are working as active resources. The ICT system consists of distribution network control centre software including SCADA and DMS (ABB MicroSCADA Pro SYS/DMS 600), aggregator software (Open EMS Suite), agents that would be located e.g. at distribution network secondary substations in real environment, the home energy management system (ThereGate), several virtual home energy management systems (PCs) and interfaces between all parts of the system. The overall architecture is depicted in Fig. 2. Currently, the demonstration environment includes only one ThereGate device, which can be used to control multiple real thermostats and switches that connect loads to the low voltage network. In order to demonstrate aggregation of active resources controlled by several home energy management systems, we have implemented virtual ThereGates to the system. In practice, the virtual ThereGates are Java programs running on different computers. The first applications, known as frequency dependent load shedding algorithm and reserve monitoring solution, have been implemented to the system.

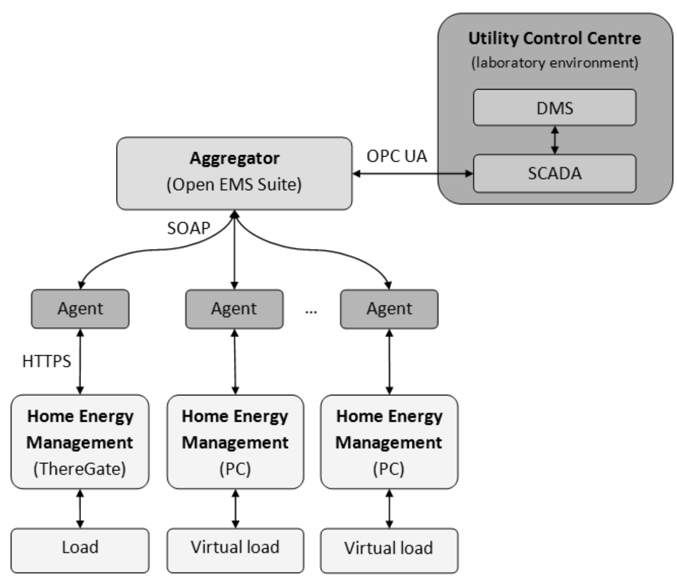

Fig. 2. Demonstration environment.

In the demonstration environment, OES and ThereGate are based on Linux platforms, whereas agents and control centre systems are running on Microsoft Windows platforms. Therefore, all chosen data transfer technologies have to be open, Web based, and platform independent in order to enable interoperability between different systems. In practice, the same requirements are necessary for all smart grid communications, as the systems may be controlled by different parties and organizations who utilize different platforms. Currently, the minimum communication delay between small-scale active resources and SCADA is one minute, whereas the maximum delay is approximately 3 minutes. Delays are mainly caused by OES and SCADA systems. For the needs of the monitoring of reserves application, the current level of communication delay is acceptable.

B. Demonstrated Applications

The demonstration consists of two applications, frequency dependent load shedding and monitoring of reserves, which are demonstrated simultaneously. The home energy management systems measure the grid frequency and make decisions about load control based on those values. In this demonstration, no real measurements are made but frequency behavior is simulated as a predefined time series. Frequency dependent load shedding algorithm reads these predefined frequency values from a text file once per second. The frequency values, which are depicted in Fig. 3, are chosen so that they cause several control actions by the frequency dependent load shedding algorithm and thereby verify the correct functionality of the algorithm.

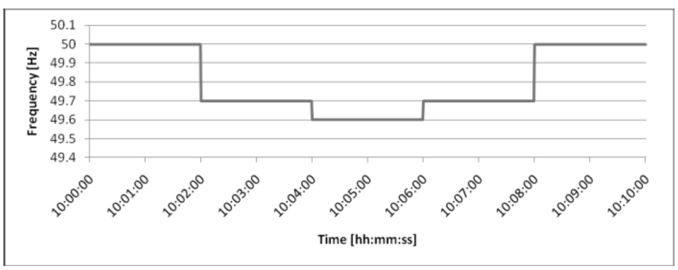

Fig. 3. Predefined frequency disturbance data.

For the needs of the monitoring of reserves application, both active power demand value and the value of loads that have been turned off by the frequency dependent load shedding algorithm, are fetched from each ThereGate once a minute by the agents, and sent to OES and ultimately to SCADA, where they are displayed in a graphical view. An example of the graphical view of SCADA is depicted in Fig. 4.

The demonstration includes one real ThereGate and one virtual ThereGate. Each ThereGate control three loads: one resistor load that represents charging of a plug-in hybrid vehicle, and two electric heaters. The real ThereGate controls real loads, whereas the virtual ThereGate controls virtual loads. The frequency dependent load shedding algorithm is designed so that it disconnects first load, an electric heating load, when frequency is equal or below 49.8 hertz. The second electric heating load is disconnected at 49.7 hertz. If the frequency still drops, the charging of a plug-in hybrid vehicle will be disconnected when the frequency is at 49.6 hertz or below. The order of disconnecting different types of loads is based on criticality of loads and customer needs. In a real environment, all loads could initially be either on or off depending on user behaviour. In the demonstration this has been taken into account by switching the state of one of the electric heater loads once during the 10 minute demonstration period.

C. Demonstration Results

The demonstration results are depicted in Fig. 4. The data transfer delay between local control actions at ThereGate level based on the frequency value (see Fig. 3) and the effect of these actions on the aggregated values on SCADA screen (see Fig. 4) is approximately 2 minutes. At the beginning of the demonstration, the frequency is 50 hertz and all six loads controlled by the ThereGates are turned on. Each load controlled by the virtual ThereGate consumes 0.5 kilowatts of active power, which makes total consumption of the virtual ThereGate equal to 1.5 kilowatts. The real ThereGate controls

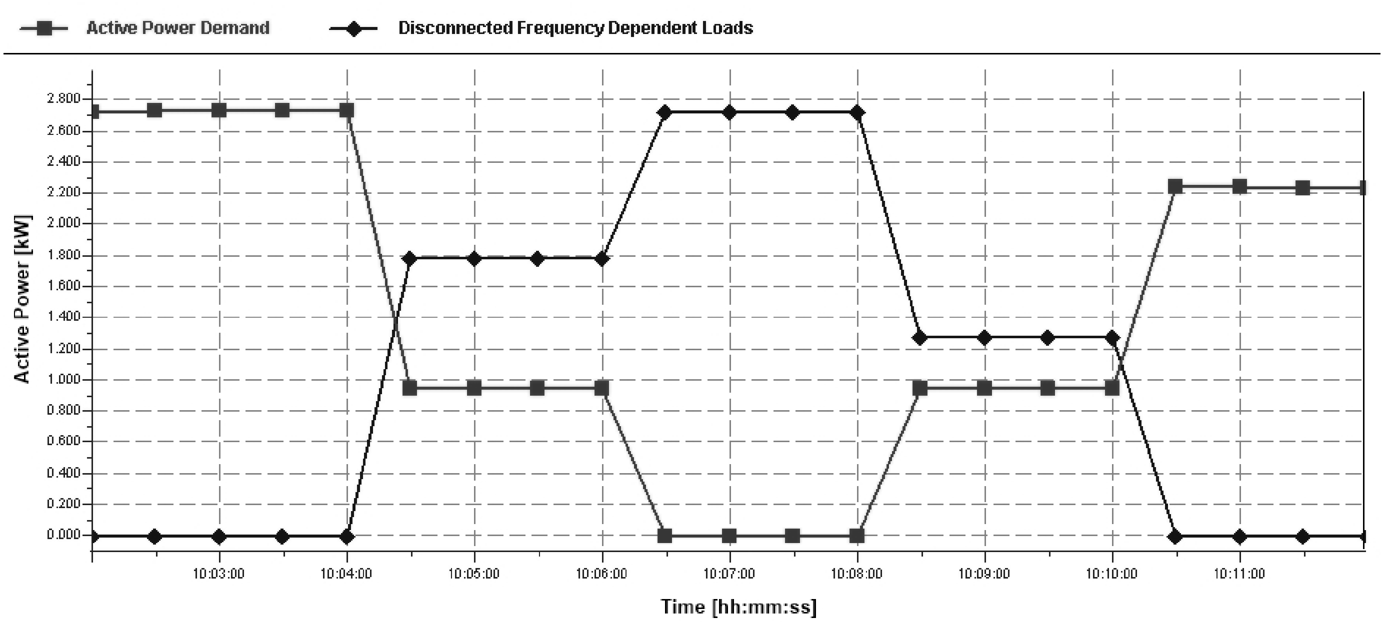

Fig. 4. Demonstration results.

three real loads, which consume approximately 1.25 kilowatts of active power in total. Therefore, the total aggregated amount of active power demand is equal to approximately 2.75 kilowatts. The amount of disconnected frequency dependent loads is naturally zero. These load values are selected for demonstration purposes only. In real life the load values would be significantly larger.

When the frequency drops to 49.7 hertz at 10:02:00 (see Fig. 3), both ThereGates disconnect two of their loads, which can be seen in Fig. 4 as a change of active power demand and disconnected frequency dependent loads values between 10:04:00 and 10:04:30. The absolute value of the change is same for both variables, because all four loads were turned off by the frequency dependent load shedding algorithm. When the frequency further decreases to 49.6 hertz at 10:04:00 (see Fig. 3), the third loads (i.e. electric vehicle charging loads), connected to both ThereGates, are turned off and the change can be seen between the timestamps of 10:06:00 and 10:06:30 in Fig. 4.

As the frequency increases back to 49.7 hertz at 10:06:00, the electric vehicle charging loads are turned back on, and the aggregated value of active power demand is updated on the SCADA screen between the timestamps of 10:08:00 and 10:08:30 (see Fig. 4). This time, the absolute values of the changes of active power demand and disconnected frequency dependent loads are not equal, because the user has turned one load manually off during the same time period, and therefore one load is no more controlled by the frequency dependent load shedding algorithm. The user behaviour can also be seen in the end of the demonstration, where the aggregated active power demand is 0.5 kilowatts (i.e. one load) smaller than at the beginning of the demonstration. As the Fig. 4 shows, the frequency dependent load shedding and the monitoring of reserves applications were successfully demonstrated by the developed smart grid management platform.

V. Future work

In the future, more applications, e.g. network overload management, will be implemented to the demonstration environment and new resources, e.g. energy storage and distributed generation, will be added. Also the existing applications will be further developed by introducing new measurements and reporting schemes in order to provide more accurate information to the aggregator and control centre systems about all events that can occur at the home energy management level. Also the information security of the developed smart grid management platform will be evaluated and improved.

VI. Conclusions

This paper defined a smart grid demonstration environment, which can be used for concept testing of different smart grid applications utilizing small-scale active resources. The demonstration environment has been successfully taken into use by implementing commercial software products and standardized data transfer technologies. Two applications, which are known as frequency dependent load shedding and monitoring of resources, have been defined and successfully demonstrated. As a result, the developed demonstration environment has been proven to be a suitable testing platform for new smart grid applications. The next step is to implement more applications and active resources to the demonstration environment.

VII. References

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VIII. Biographies

Antti Koto was born in Mustasaari, Finland, on March 4, 1984. He received his Master's Degree in electrical engineering from Tampere University of Technology in 2010.

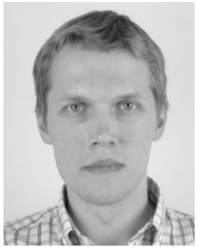
Currently he is a researcher and a post-graduate student at the Department of Electrical Energy Engineering of Tampere University of Technology. His main interest is the data transfer between information systems in distribution network operations.

Shengye Lu has two M.Sc. degrees in Computer Science and Engineering, received from Aalto University, Finland in 2011 and from Southeast University, China in 2006 respectively.

Currently she is a researcher and a post-graduate student at the Department of Electrical Energy Engineering of Tampere University of Technology. Her main interests are aggregator software and communication solutions for Smart Grid applications.

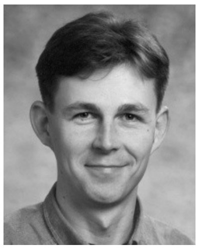
Turo Valavaara was born in Tampere, Finland, on April 11, 1987. He received his Bachelor's Degree in automation engineering from Tampere University of Technology in 2011.

Currently he is a research assistant at the Department of Electrical Energy Engineering of Tampere University of Technology. He is also studying for his Master's degree at Tampere University of Technology, concentrating on studies of software technology.



Antti Rautiainen received his M.Sc. degree from Tampere University of Technology in 2008.

He is now working as a researcher towards doctoral degree at the Department of Electrical Energy Engineering of Tampere University of Technology. His main interest focuses on the effects of plug-in vehicles to electric power systems, ancillary service possibilities of plug-in vehicles and new load control schemes.



Sami Repo received his M.Sc. and Dr.Tech. degrees in electrical engineering from Tampere University of Technology, Finland, in 1996 and 2001 respectively.

At present he is an associate professor at the Department of Electrical Energy Engineering of Tampere University of Technology. His main interest is the management of active distribution network including distributed energy resources.